Decoherence and entanglement degradation of a qubit-qutrit system in non-inertial frames

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We study the effect of decoherence on a qubit-qutrit system under the influence of global, local and multilocal decoherence in non-inertial frames. We show that the entanglement sudden death can be avoided in non-inertial frames in the presence of amplitude damping, depolarizing and phase damping channels. However, degradation of entanglement is seen due to Unruh effect. It is shown that for lower level of decoherence, the depolarizing channel degrades the entanglement more heavily as compared to the amplitude damping and phase damping channels. However, for higher values of decoherence parameters, amplitude damping channel heavily degrades the entanglement of the hybrid system. Further more, no ESD is seen for any value of Rob's acceleration.

I. INTRODUCTION

Quantum information and quantum computation can process multiple tasks which are intractable with classical technologies. Quantum entanglement is no doubt a fundamental resource for a variety of quantum information processing tasks, such as super-dense coding, quantum cryptography and quantum error correction [1-4]. Strongly entangled, multi-partite states of qubits and qutrits are a central resource of quantum information science. These are frequently used in constructing many protocols, such as teleportation [5], key distribution and quantum computation [6]. The phenomenon of sudden loss of entanglement also termed as "entanglement sudden death" ESD has been investigated by a number of authors for bipartite and multipartite systems [7-10]. Yu and Eberly [11, 12] showed that entanglement loss occurs in a finite time under the action of pure vacuum noise in a bipartite state of qubits. They found that, even though it takes infinite

time to complete decoherence locally, the global entanglement may be lost in finite time.

Recently, researchers have focused on relativistic quantum information in the filed of quantum information science due to conceptual and experimental reasons. In the last few years, much attention had been given to the study of entanglement shared between inertial and non-inertial observers by discussing how the Unruh or Hawking effect will influence the degree of entanglement [13–22]. Most of the investigations in non-inertial frames are focused on the study of the quantum information in bipartite qubit system with one subsystem as an accelerated. Since, it is not possible to completely isolate a quantum system from its environment. Therefore, one needs to investigate the behavior of entanglement in the presence of environmental effects. A major problem of quantum communication is to faithfully transmit unknown quantum states through a noisy quantum channel. When quantum information is sent through a channel, the carriers of the information interact with the channel and get entangled with its many degrees of freedom. This gives rise to the phenomenon of decoherence on the state space of the information carriers. Implementation of decoherence in non-inertial frames have been investigated by different authors [23, 24]. Peres-Horodecki [25, 26] have studied entanglement of qubit-qubit and qubit-qutrit states and established separability criterion. According to this criterion, the partial transpose of a separable density matrix must have non-negative eigenvalues, where the partial transpose is taken over the smaller subsystem for qubit-qutrit case. For nonseparable states, the sum of the absolute values of the negative eigenvalues of the partial transpose gives the degree of entanglement of a density matrix also termed as negativity. Ann et al. [27] have studied a qubit-qutrit system where they have shown the existence of ESD under the influence of dephasing noise.

In this paper, we study the effect of decoherence on a qubit-qutrit system in non-inertial frames by considering different noise models, such as, amplitude damping, depolarizing and phase damping channels. We consider different couplings of the system and the environment where the system is influenced by global, local, or multi-local noises modeled in a number of scenarios. We show that entanglement degradation occurs for various coupling of the system and the environment. It is shown that different environments degrade the entanglement of the hybrid system differently.

II. QUBIT-QUTRIT SYSTEM IN NON-INERTIAL FRAMES

We consider a composite system of a qubit A and a qutrit B that is coupled to a noisy environment both collectively and individually. Local and multi-local couplings describe the situation when the qubit and qutrit are independently influenced by their individual noisy environments.

Whereas, the global decoherence corresponds to the situation when it is influenced by both collective and multilocal noises at the same time. The term collective coupling means when both the qubit and qutrit are influenced by the same noise. The state shared by the two parties is an entangled qubit-qutrit state of the form [28]

$$\rho_{AR} = \frac{1}{2} \begin{pmatrix} \cos^2 r(|01\rangle_{AR}\langle 01| + |01\rangle_{AR}\langle 10| + |10\rangle_{AR}\langle 01| + |10\rangle_{AR}\langle 10|) \\ + \sin^2 r(|02\rangle_{AR}\langle 02| + |12\rangle_{AR}\langle 12|) \end{pmatrix} \tag{1}$$

where the two modes of Minkowski spacetime that correspond to Alice and Rob are $|\eta\rangle_A$ and $|\eta\rangle_R$ respectively. We assume that Alice remain stationary while Rob moves with uniform acceleration. It is important to mention here that the above state is obtained after taking the trace over unobserved region IV [28]. The interaction between the system and its environment introduces the decoherence to the system, which is a process of the undesired correlation between the system and the environment. The evolution of a state of a quantum system in a noisy environment can be described by the super-operator Φ in the Kraus operator representation as [29]

$$\rho_f = \Phi\rho_i = \sum_k E_k \rho_i E_k^\dagger \tag{2}$$

where the Kraus operators E_i satisfy the following completeness relation

$$\sum_k E_k^\dagger E_k = I \tag{3}$$

We have constructed the Kraus operators for the evolution of the composite system from the single qubit Kraus operators (see table1) and qutrit Kraus operators as given in equations (5-8) by taking their tensor product over all $n \otimes m$ combination of $\pi(i)$ indices

$$E_k = \underset{\pi}{\otimes} e_{\pi(i)} \tag{4}$$

where n and m correspond to the number of Kraus operators for a single qubit and qutrit channel respectively. The single qutrit Kraus operators for the amplitude damping channel are given by [30]

$$E_0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sqrt{1-p} & 0 \\ 0 & 0 & \sqrt{1-p} \end{pmatrix}, \quad E_1 = \begin{pmatrix} 0 & \sqrt{p} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad E_2 = \begin{pmatrix} 0 & 0 & \sqrt{p} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{5}$$

and the single qutrit Kraus operators for the phase damping channel are given as

$$E_0 = \sqrt{1-p} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad E_1 = \sqrt{p} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix}, \tag{6}$$

The single qutrit Kraus operators for the depolarizing channel are given by [31]

$$E_0 = \sqrt{1-p}I_3, \ E_1 = \sqrt{\frac{p}{8}}Y, \ E_2 = \sqrt{\frac{p}{8}}Z, \ E_3 = \sqrt{\frac{p}{8}}Y^2, \ E_4 = \sqrt{\frac{p}{8}}YZ$$

$$E_5 = \sqrt{\frac{p}{8}}Y^2Z, \ E_6 = \sqrt{\frac{p}{8}}YZ^2, \ E_7 = \sqrt{\frac{p}{8}}Y^2Z^2, \ E_8 = \sqrt{\frac{p}{8}}Z^2 \tag{7}$$

where I_3 is the identity matrix of order 3.

$$Y = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \quad Z = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix} \tag{8}$$

In the above equations, p represents the quantum noise parameter and $\omega = e^{\frac{2\pi i}{3}}$. The evolution of the initial density matrix of the composite system when it is influenced by local and multi-local environments is given in Kraus operator form as

$$\rho_f = \sum_{i,j,k} (E_j^B E_k^A)\rho_{AR}(E_j^B E_k^A)^\dagger \tag{9}$$

and the evolution of the system when it is influenced by global environment is given in Kraus operator representation as

$$\rho_f = \sum_{i,j,k} (E_i^{AB} E_j^B E_k^A)\rho_{AR}(E_i^{AB} E_j^B E_k^A)^\dagger \tag{10}$$

where $E_k^A = E_m^A \otimes I_3$, $I_2 \otimes E_j^B$ are the Kraus operators of the multilocal coupling of qubit and qutrit individually and $E_i^{AB} = E_m^A \otimes E_n^A$ are the Kraus operators of the collective coupling of the hybrid system. Using equations (5-10) along with the initial density matrix of as given in equation (1) and taking the partial transpose over the smaller subsystem (qubit), we find the eigenvalues of the final density matrix. Let the decoherence parameters for local and global noise of the qubit and

qutrit be p_1, p_2 and p respectively. The entanglement for all mixed states ρ_{AB} of a qubit-qutrit system is well quantified by the negativity [32]

$$N(\rho_{AB}) = \max\{0, \sum_k \left|\lambda_k^{T_A(-)}\right|\}) \tag{11}$$

where $\lambda_k^{T_A(-)}$ represents the negative eigenvalues of the partial transpose of the density matrix ρ_{AB} with respect to the smaller subsystem. The eigenvalues of the partial transpose matrix when only the qubit is influenced by the amplitude damping channel are given by

$$
\begin{aligned}
\lambda_{1,2} &= \frac{1}{2}\cos^2 r \\
\lambda_3 &= -\frac{1}{2}(-1+p_1)\cos^2 r \\
\lambda_4 &= \frac{1}{2}(-1+p_1)\cos^2 r \\
\lambda_5 &= -\frac{1}{2}(-1+p_1)\sin^2 r \\
\lambda_6 &= \frac{1}{2}(-1+p_1)\sin^2 r
\end{aligned}
\tag{12}
$$

The only possible negative eigenvalue is the fourth one and the negativity is calculated using the relation given in equation (11). The eigenvalues of the partial transpose matrix when only qutrit is influenced by the amplitude damping channel are given by

$$
\begin{aligned}
\lambda_1 &= -\frac{1}{2}(-1+p_2)\cos^2 r \\
\lambda_{2,3} &= \frac{1}{4}(p_2 \mp \sqrt{p_2^2 - 4(-1+p_2)\cos^4 r}) \\
\lambda_{4,5} &= -\frac{1}{2}(-1+p_2)\sin^2 r \\
\lambda_6 &= \frac{1}{2}(\cos^2 r + p_2\sin^2 r)
\end{aligned}
\tag{13}
$$

The only possible negative eigenvalue is the second one. The eigenvalues of the partial transpose matrix when both qubit and qutrit are influenced by the amplitude damping channel are given by

$$
\begin{aligned}
\lambda_1 &= -\frac{1}{2}(-1+p_2)\cos^2 r \\
\lambda_2 &= \frac{1}{2}(-1+p_1)(-1+p_2)\sin^2 r \\
\lambda_3 &= -\frac{1}{2}(1+p_1)(-1+p_2)\sin^2 r \\
\lambda_4 &= -\frac{1}{2}(-1+p_1)(\cos^2 r + p_2\sin^2 r) \\
\lambda_{5,6} &= \left(\begin{array}{c} \frac{1}{8}(p_1 + 2p_2 + p_1 p_2 + p_1\cos(2r) - p_1 p_2\cos(2r)) \\ \mp 2\sqrt{\begin{array}{l} 4(-1+p_1)(-1+p_2)\cos^4 r + \\ ((p_1+p_2)\cos^2 r + (1+p_1)p_2\sin^2 r)^2 \end{array}}\,\big] \end{array}\right)
\end{aligned}
\tag{14}
$$

The only possible negative eigenvalue is the fifth one. The eigenvalues of the partial transpose matrix when the system is influenced by the global noise of amplitude damping channel are given by

$$\lambda_1 = \frac{1}{2}(-1+p)(-1+p_2)\cos^2 r$$

$$\lambda_2 = \frac{1}{4}(-1+p_1)^2(1+p+p_2-pp_2+(-1+p)(-1+p_2)\cos(2r))$$

$$\lambda_3 = \frac{1}{2}(-1+p)(-1+p_1)^2(-1+p_2)\sin^2 r$$

$$\lambda_4 = -\frac{1}{2}(-1+p)(-1-2p_1+p_1^2)(-1+p_2)\sin^2 r$$

$$\lambda_{5,6} = \left(\begin{array}{c} \frac{1}{4}[p\cos^2 r + 2p_1\cos^2 r - p_1^2\cos^2 r + +p_2\cos^2 r - pp_2\cos^2 r \\ +p\sin^2 r + 2pp_1\sin^2 r - pp_1^2\sin^2 r + p_2\sin^2 r - pp_2\sin^2 r \\ +2p_1p_2\sin^2 r - 2pp_1p_2\sin^2 r - p_1^2p_2\sin^2 r + pp_1^2p_2\sin^2 r \\ \hline \\ \mp \sqrt{\begin{array}{c} 4(-1+p)(-1+p_1)^2(-1+p_2)\cos^4 r \\ +((-2p_1+p_1^2+p(-1+p_2)-p_2)\cos^2 r \quad] \\ -(-1-2p_1+p_1^2)(p(-1+p_2)-p_2)\sin^2 r)^2 \end{array}} \end{array} \right) \quad (15)$$

The only possible negative eigenvalue is the fifth one. The eigenvalues of the partial transpose matrix when only the qubit is influenced by the depolarizing channel are given by

$$\lambda_{1,2} = \frac{1}{2}\sin^2 r$$

$$\lambda_3 = \frac{1}{4}(-2\cos^2 r + 3p_1\cos^2 r)$$

$$\lambda_{4,5,6} = -\frac{1}{4}(-2+p_1)\cos^2 r \quad (16)$$

The only possible negative eigenvalue is the third one. The eigenvalues of the partial transpose matrix when only qutrit is influenced by the depolarizing channel are given by

$$\lambda_{1,2,3} = \frac{1}{32}(8-3p_2+8\cos(2r)-9p_2\cos(2r))$$

$$\lambda_4 = \frac{1}{32}(-8+15p_2-8\cos(2r)+9p_2\cos(2r))$$

$$\lambda_{5,6} = \frac{1}{32}(8-3p_2+(-8+9p_2)\cos(2r)) \quad (17)$$

The only possible negative eigenvalue is the fourth one. The eigenvalues of the partial transpose matrix when both the qubit and the qutrit are influenced by the depolarizing channel are given by

$$
\begin{aligned}
\lambda_{1,2} &= \frac{1}{32}(8 - 3p_2 + (-8 + 9p_2)\cos(2r)) \\
\lambda_{3,4} &= \frac{1}{32}((16 - 12p_2 + p_1(-8 + 9p_2))\cos^2 r + 6p_2\sin^2 r) \\
\lambda_{5,6} &= \begin{pmatrix} \frac{1}{64}(8p_1 + 12p_2 - 9p_1p_2 \mp 2\sqrt{2}\sqrt{2(-1 + p_1)^2(8 - 9p_2)^2\cos^4 r} \\ +8p_1\cos(2r) - 9p_1p_2\cos(2r)) \end{pmatrix}
\end{aligned}
\tag{18}
$$

The only possible negative eigenvalue is the fifth one. The eigenvalues of the partial transpose matrix when the system is influenced by the global noise of depolarizing channel are given by

$$
\begin{aligned}
\lambda_{1,2} &= \begin{pmatrix} \frac{1}{512}(96p + 128p_1 - 144pp_1 - 64p_1^2 + 72pp_1^2 + 96p_2 - 108pp_2 - 144p_1p_2 \\ +162pp_1p_2 + 72p_1^2p_2 - 81pp_1^2p_2 \mp 2\sqrt{2}\sqrt{2(8 - 9p)^2(-1 + p_1)^4(8 - 9p_2)^2\cos^4 r} \\ +128p_1\cos(2r) - 144pp_1\cos(2r) - 64p_1^2\cos(2r) + 72pp_1^2\cos(2r) \\ -144p_1p_2\cos(2r) + 162pp_1p_2\cos(2r) + 72p_1^2p_2\cos(2r) - 81pp_1^2p_2\cos(2r)) \end{pmatrix} \\
\lambda_{3,4} &= \frac{1}{256}(64 - 24p_2 + 3p(-8 + 9p_2) - (-8 + 9p)(-8 + 9p_2)\cos(2r)) \\
\lambda_{5,6} &= \begin{pmatrix} \frac{1}{256}((3p(4 - 6p_1 + 3p_1^2)(-8 + 9p_2) - 8(4(-4 + 3p_2) - 2p_1(-8 + 9p_2) \\ +p_1^2(-8 + 9p_2)))\cos^2 r + 6(p(8 - 9p_2) + 8p_2)\sin^2 r) \end{pmatrix}
\end{aligned}
\tag{19}
$$

The only possible negative eigenvalue is the first one. The eigenvalues of the partial transpose matrix when only qubit is influenced by the phase damping channel are given by

$$
\begin{aligned}
\lambda_{1,2} &= \frac{1}{2}\cos^2 r \\
\lambda_3 &= -\frac{1}{2}\sqrt{\cos^4 r - p_1\cos^4 r} \\
\lambda_4 &= \frac{1}{2}\sqrt{\cos^4 r - p_1\cos^4 r} \\
\lambda_{5,6} &= \frac{1}{2}\sin^2 r
\end{aligned}
\tag{20}
$$

The only possible negative eigenvalue is the third one. The eigenvalues of the partial transpose matrix when only qutrit is influenced by the phase damping channel are given by

$$
\begin{aligned}
\lambda_{1,2} &= \frac{1}{2}\cos^2 r \\
\lambda_3 &= -\frac{1}{2}\sqrt{(1 - 3p_2 + 3p_2^2)\cos^4 r} \\
\lambda_4 &= \frac{1}{2}\sqrt{(1 - 3p_2 + 3p_2^2)\cos^4 r} \\
\lambda_{5,6} &= \frac{1}{2}\sin^2 r
\end{aligned}
\tag{21}
$$

The only possible negative eigenvalue is the third one. The eigenvalues of the partial transpose matrix when both qubit and qutrit are influenced by the phase damping channel are given by

$$
\begin{aligned}
\lambda_{1,2} &= \frac{1}{2}\cos^2 r \\
\lambda_3 &= -\frac{1}{2}\sqrt{(-1+p_1)(-1+3p_2-3p_2^2)\cos^4 r} \\
\lambda_4 &= \frac{1}{2}\sqrt{(-1+p_1)(-1+3p_2-3p_2^2)\cos^4 r} \\
\lambda_{5,6} &= \frac{1}{2}\sin^2 r
\end{aligned}
\tag{22}
$$

The only possible negative eigenvalue is the third one. The eigenvalues of the partial transpose matrix when the system is influenced by the global noise of phase damping channel are given by

$$
\begin{aligned}
\lambda_{1,2} &= \frac{1}{2}\cos^2 r \\
\lambda_3 &= -\frac{1}{2}\sqrt{(1-3p+3p^2)(-1+p_1)^2(1-3p_2+3p_2^2)\cos^4 r} \\
\lambda_4 &= \frac{1}{2}\sqrt{(1-3p+3p^2)(-1+p_1)^2(1-3p_2+3p_2^2)\cos^4 r} \\
\lambda_{5,6} &= \frac{1}{2}\sin^2 r
\end{aligned}
\tag{23}
$$

The only possible negative eigenvalue is the third one. The negativity is calculated using equation (5) for all the above cases and results are discussed in detail in the next section.

III. DISCUSSIONS

In this work, we investigate the effect of decoherence on a qubit-qutrit system in non-inertial frames. In figure 1, we plot negativity as a function of Rob's acceleration, r for decoherence parameters $p_i = 0.2$ for amplitude damping channel. It is seen that maximal entanglement degradation occurs under global noise. It is also seen that the entanglement is degraded heavily as we increase the value of Rob's acceleration. However, the entanglement loss is consistent for all the cases and no ESD behaviour is seen for any acceleration. In figure 2, we plot the negativity as a function of Rob's acceleration, r for $p_1 = p_2 = 0.2$ (multi-local noise) and $p = 0.2$ (global noise) for depolarizing channel. It is seen that depolarizing channel heavily degrades the entanglement as compared to amplitude damping channel, particularly in case of global decoherence. In figure 3, we plot the negativity as a function of Rob's acceleration, r for $p_1 = p_2 = 0.2$ (multi-local noise) and $p = 0.2$ (global noise) for phase damping channel. A similar behaviour of amplitude damping and phase damping channels is seen towards entanglement degradation.

In figure 4, we plot the negativity as a function of Rob's acceleration, r for $p_1 = p_2 = p = 0.2$ for amplitude damping, depolarizing and phase damping channels. It is shown that depolarizing channel influences the entanglement of the system more heavily as compared to the other two channels. On the other hand, for higher values of decoherence parameters, the amplitude damping channel have more influence on the entanglement degradation as clear from figure 5. Further more, it is also seen that no ESD occurs for any acceleration of Rob for the entire range of decoherence parameters.

IV. CONCLUSIONS

We analyze the effect of decoherence on a qubit-qutrit system under the influence of decoherence in non-inertial frames. We consider different noise models such as amplitude damping, depolarizing and phase damping channels with different couplings of the system and the environment. We show that the entanglement sudden death can be avoided in non-inertial frames. However, degradation of entanglement is seen due to Unruh effect. It is seen that for lower values of decoherence parameters, the depolarizing channel heavily degrades the entanglement of the system as compared to the amplitude damping and phase damping channels. However, for higher values of decoherence parameters, amplitude damping channel heavily degrades the entanglement of the system. In conclusion, no ESD occurs for any value of Rob's acceleration.

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Figures captions

Figure 1. The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = 0.2$ (multi-local noise) and $p = 0.2$ (global noise) for amplitude damping channel.

Figure 2. The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = 0.2$ (multi-local noise) and $p = 0.2$ (global noise) for depolarizing channel.

Figure 3. The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = 0.2$ (multi-local noise) and $p = 0.2$ (global noise) for phase damping channel.

Figure 4. The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = p = 0.2$ for amplitude damping, depolarizing and phase damping channels.

Figure 5. The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = p = 0.5$ for amplitude damping, depolarizing and phase damping channels.

Table Caption

Table 1. Single qubit Kraus operators for amplitude damping, depolarizing and phase damping channels where p represents the decoherence parameter.

TABLE I: Single qubit Kraus operators for amplitude damping, depolarizing and phase damping channels where p represents the decoherence parameter.

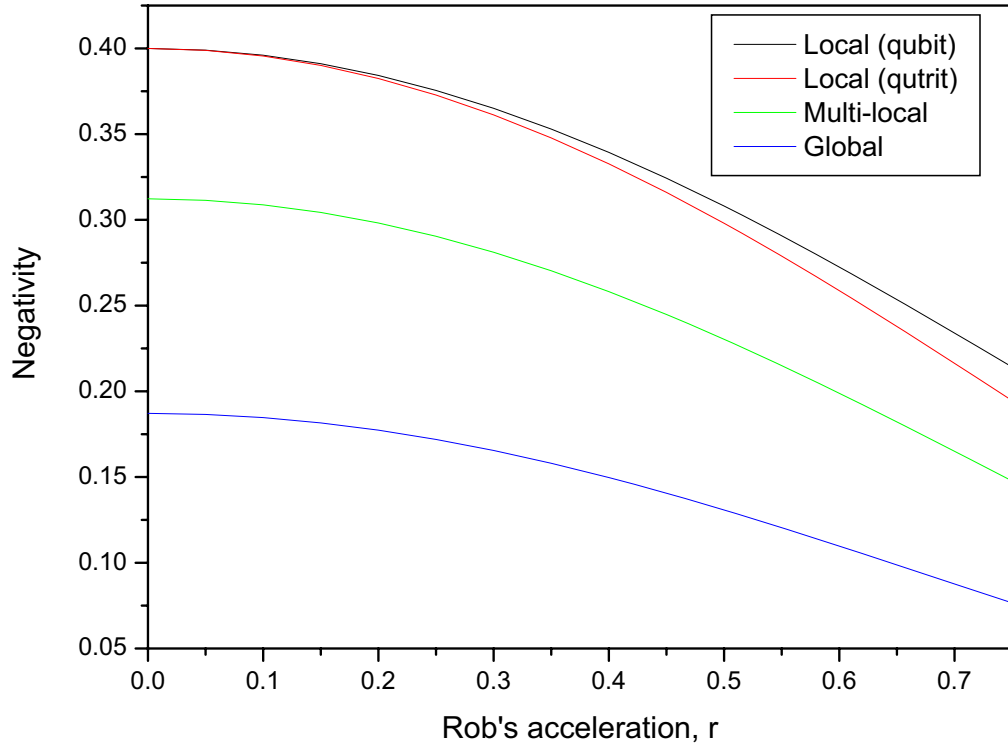|	
Depolarizing channel	$E_0 = \sqrt{1 - \frac{3p}{4}}I, \quad E_1 = \sqrt{\frac{p}{4}}\sigma_x$ $E_2 = \sqrt{\frac{p}{4}}\sigma_y, \qquad E_3 = \sqrt{\frac{p}{4}}\sigma_z$
Amplitude damping channel	$E_0 = \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-p} \end{bmatrix}, E_1 = \begin{bmatrix} 0 & \sqrt{p} \\ 0 & 0 \end{bmatrix}$
Phase damping channel	$E_0 = \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-p} \end{bmatrix}, E_1 = \begin{bmatrix} 0 & 0 \\ 0 & \sqrt{p} \end{bmatrix}$

FIG. 1: The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = 0.2$ (multi-local noise) and $p = 0.2$ (global noise) for amplitude damping channel.
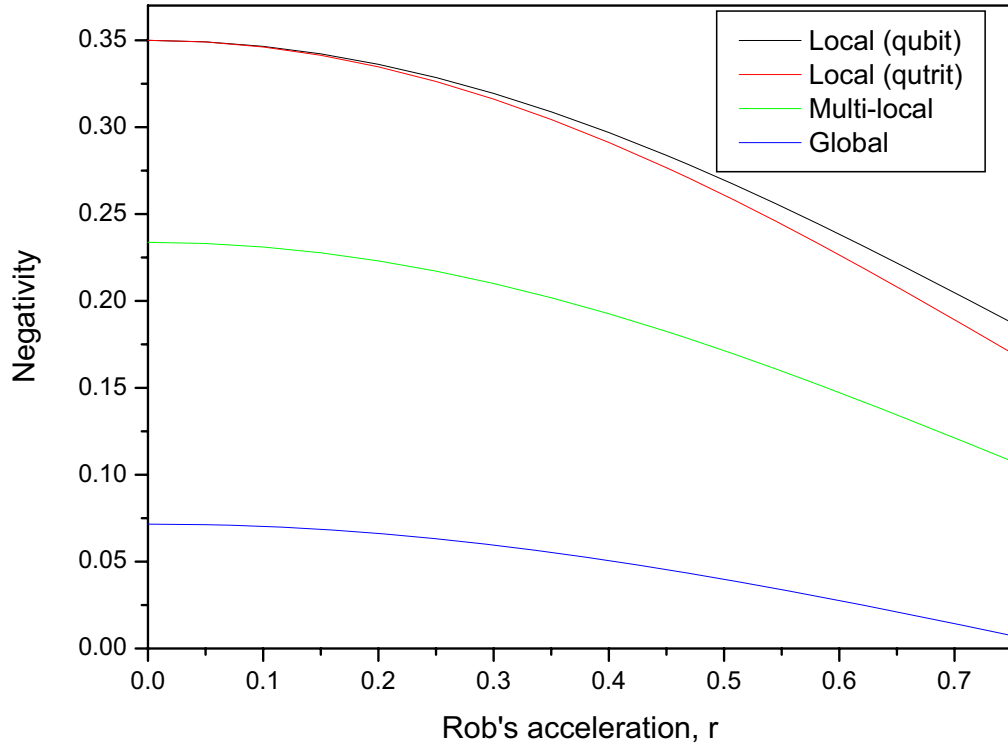
FIG. 2: The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = 0.2$ (multi-local noise) and $p = 0.2$ (global noise) for depolarizing channel.
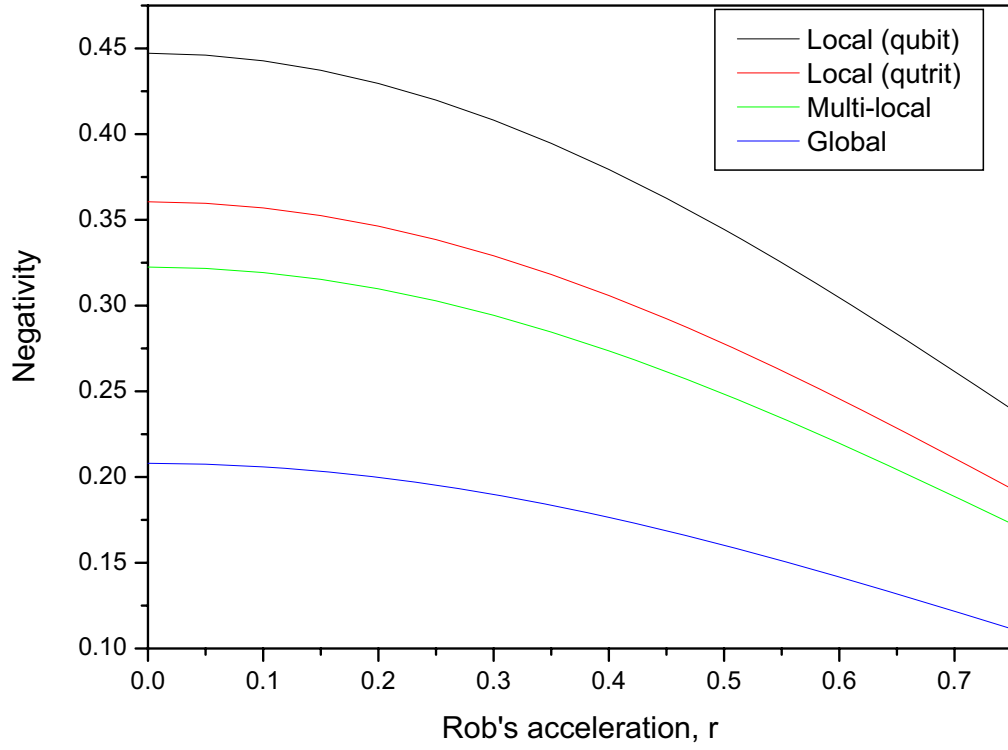
FIG. 3: The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = 0.2$ (multi-local noise) and $p = 0.2$ (global noise) for phase damping channel.
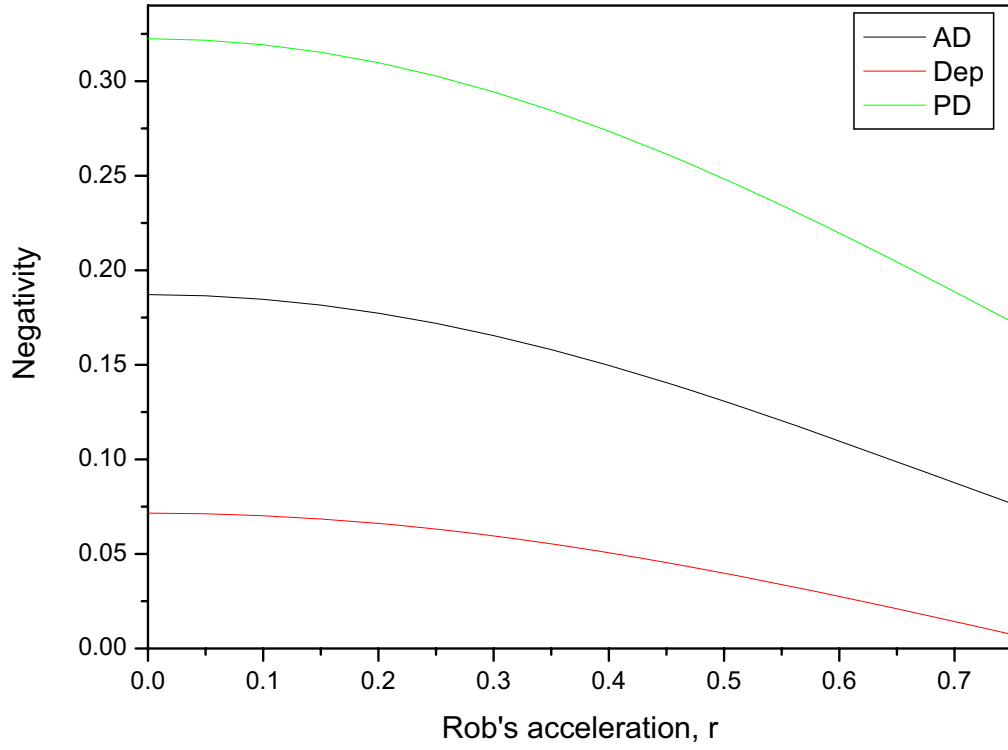
FIG. 4: The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = p = 0.2$ for amplitude damping, depolarizing and phase damping channels.
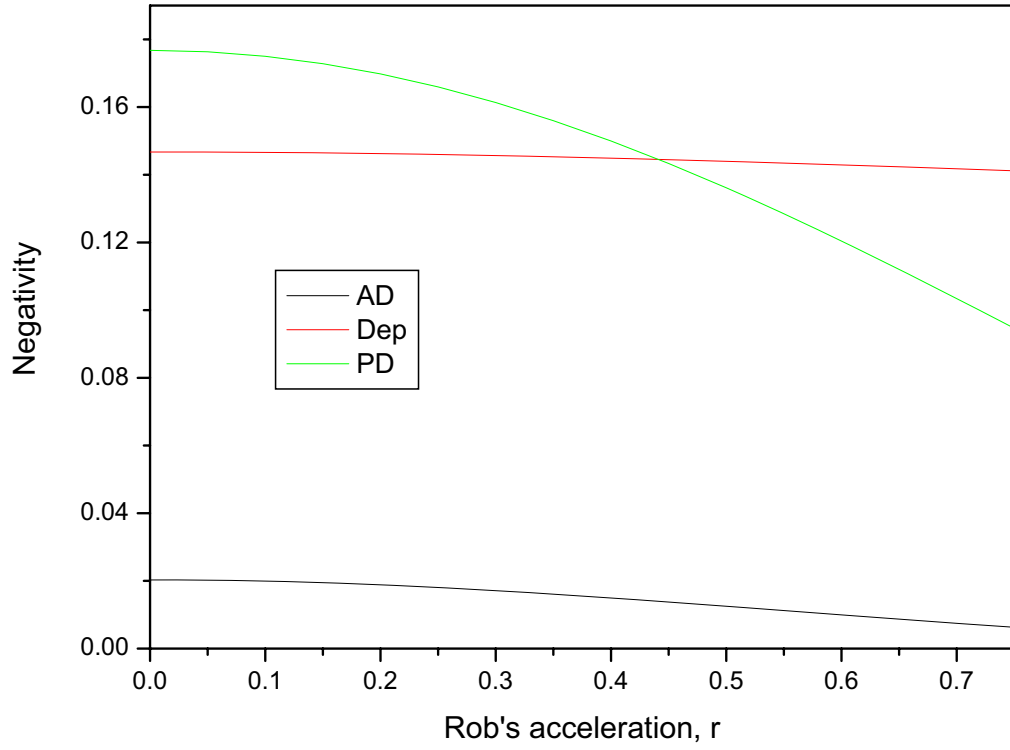
FIG. 5: The negativity is plotted as a function of Rob's acceleration, r for $p_1 = p_2 = p = 0.5$ for amplitude damping, depolarizing and phase damping channels.